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Research Article

Phosphorus sorption characteristics of lime amended Ultisols and Alfisols in humid tropical Western Ethiopia

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Abstract

Ultisols and Alfisols in humid Western Ethiopia are deficient in available phosphorus (P) but respond slightly to P fertilization. The study determined P sorption characteristics of five soils with and without optimum lime rate. Phosphorus sorption was conducted by equilibrating the soils with P solutions. Phosphorus sorption patterns of unlimed soils had no sorption maxima while limed soils had sorption maxima. The sorption data fitted to Langmuir model. The unlimed and limed soils had high P sorption capacity. The net zero equilibrium P concentration (EPC0) ranged from 0.007 to 0.012mg l^{-1}. Standard phosphorus requirement (SPR) ranged from 759 to 831 and 441 to 1164mg kg^{-1} for soils and lime treatments, respectively. Langmuir adsorption maxima (bmax) ranged from 2072 to 2792 and 2352 to 2367mg kg^{-1} for soils and lime effect, respectively. Effect of soil types on sorption was not significant while lime significantly decreased SPR from 1164 to 441mg k g^{-1}. The bmax of Alfisols increased while of Ultisols decreased with liming. The study suggested that Alfisols and Ultisols require 39 to 49 kg ha^{-1} and 63 to 75kg ha^{-1} to elevate solution P concentration to 0.1 and 0.2mg l^{-1}, respectively. The study indicated that P fertilizer recommendations for most agronomic crops in Ethiopia were lower than SPR. With optimal lime rate, the recommended P fertilizer provides suboptimal SPR to provide 0.1 mg l^{-1} but require additional P fertilizer to achieve 0.2mg l^{-1}. With optimum lime rate, P fertilizer recommendations should be developed through research for Alfisols and Ultisols of humid Western Ethiopia.

Keywords: Langmuir model; Net zero equilibrium P concentration; Sorption maxima; Standard phosphorus requirement; Typic Ferrudalfs: Typic Hapludults

Introduction

Oxisols, Ultisols and Alfisols are weathered acid tropical soils Soil Survey Staff [1] which have high phosphorus (P) sorption capacity. In the weathered soils, P is bound to oxides of Fe and Al, and clay minerals [2,3] and it consequently becomes less bioavailable [2-4]. Phosphorus sorption and occlusion deplete available P form, decrease P fertility of soils and soils become P deficient under severe cases. The availability of applied P as fertilizer is governed by quantity-intensity (Q-I) factors. The quantity factor is the labile P pool that is in equilibrium with soil solution P [5,6]. The intensity factor represents P in soil solution. Plethora of literatures show weathered tropical soils have varying Q-I factors and P adsorption capacities. For example, the adsorption capacity ranged from 110 to 405 mg kg^{-1} for Latosols of the Cerrado area of Brazil [7], 71 to 500 mg kg^{-1} for some soils of Australia Ahmed, 192 to 909 mg kg^{-1} for some Oxisols and Alfisols of South Africa [8], 315 to 413 mg kg^{-1} for Oxisols and Ultisols of Malawi of Central Africa [9], and 80 to 917 mg kg^{-1} for some Sudanese soils of East Africa [10].

Phosphorus sorption isotherm is a common method to determine Q-I factors, hence the sorption capacity of native soils and the fate of applied P fertilizer to soil system. It helps to determine the standard P requirements (SPR) of soils, which is the amount of added P as fertilizers to supply adequate P ions to meet the plant demand of 0.1 to 0.2 mg l^{-1} of soil solution concentration [4 &9-13]. Phosphorus sorption isotherm is also useful in the prediction of dissolved P movement to surface water through runoff and leaching.

Sorption of P increases with weathering intensity of soils [6]. Although wide variability exists among various soil groups over spatial scale, Oxisols and Ultisols have generally high P adsorption capacities and high SPR to supply optimum soil solution P for proper growth of crops and have very low equilibrium P concentration at which net sorption and desorption become zero (EPC0) [4,8-11]. Soil groups at intermediate stage of weathering such as Vertisols, Aridisols and Cambisols have intermediate P sorption capacities and SPR [4&10-14] . Soils that differ in the initial P concentration of soil solution, pH, clay mineralogy, and (hydr)oxides show different P sorption capacities, SPR, and P fertilizer demand [8,15,16]. Eastern Africa is characterized by heterogeneous pedo-environment and P sorption studies have been conducted to determine the P sorption capacity and SPR of various soil groups [10,12,13]. The studies have revealed that many soil taxonomic groups of the region with varying mineralogical composition, weathering intensity and soil reaction have both high P sorption and toxicity problem associated with release of soluble Al and Mn from hydrous oxides of these elements at low pH.

Liming is a common method to decrease P sorption capacity through increasing soil pH to neutrality [17]. Lime as amendment of acid soils decreases phosphate adsorption and promotes precipitation of Al compounds as gibbsite, and stimulates mineralization of organic P. Thus, lime as amendment increases phosphate bioavailability. Various research reports are globally available on benefit of lime as soil amendment to decrease high adsorption capacity of Al and Mn oxides and hydroxides for applied P from soil system [17,18]. Currently, meager results are currently available in East Africa on the effect of lime treatment of acid soils on reduction of P adsorption among different taxonomic groups [2,19].

Ultisols and Alfisols are the major soils in Ethiopia [20]. These soil groups are extremely to very strongly acidic, have low available P and a high P sorption capacity and high SPR [15]. As a result, continuous negative P balance in agricultural soils of this region attributed to these adverse soil characteristics. In addition to ameliorating soil acidity and Al toxicity, liming as amendment decreases P adsorption and enhance soil fertility [21-23].

Liming research in Ethiopia date back to early 1980's with the attempt to raise pH of acid soils rich in exchangeable Al to neutrality and to improve nutrient availability. Impressive plant growth and yield response were reported by Mesfin [24] due to lime treatment of acid soils. For example, study conducted at Gimbi and Nejo on strongly acid soils of Ethiopia revealed that liming combined with NP fertilizer application significantly increased agronomic yields of many crops [24,25]. At Chencha of Southern Ethiopia, liming also significantly increased agronomic yield of barley [24,25]. Significant yield increments of finger millet and maize were also reported in Wollega zones with application of 3 tons of $CaCO_3$ with supplementary N and P fertilization [25]. Tuber yield of Irish potato was significantly increased by liming acid soils with 3.5 tons per ha^{-1} with NPK rate of 110:40:100 kg ha^{-1} in Southern Ethiopia [26]. However, liming did not significantly increase yields of wheat, soybean and haricot bean [24]. These conflicting results might be attributed to increased P sorption due to liming which can happen under certain circumstances [17]. when new surface for P sorption is created upon precipitation of exchangeable Al.

In various earlier liming studies conducted in 1980's, 3 tons ha^{-1} of lime was tentatively recommended which however was not translated into action to reclaim soil acidity. Liming acid soils in Ethiopia was reinitiated as the Ethiopian government recognized the adverse effect of soil acidity and developed policy strategy of liming acid soils. Plethora of research has recently been conducted to determine lime requirement (LR) of acidic soils [26-33]. The results have revealed that lime requirement of acidic soils varies with the level of exchangeable Al, soil pH, clay and oxides and hydroxides Al and Mn. In acid soils of Ethiopia, particularly Ultisols and Alfisols, the effect of optimum lime as amendment on P sorption parameters is lacking. Therefore, the objective of the study was to determine the effect of optimum lime rate on P sorption characteristics of soils in acidic Ultisols and Alfisols, from humid tropical Ethiopia.

Materials and Methods

a. Description of Study Area

The study was conducted in Didessa sub basin of Ethiopia Figure 1. Soil samples were collected from toposequence of Didessa watershed that ranges from plateau (9°06'12.7180" N, 36°28'22.1868" E) to graben (8°40'1.9920"N, 36°25'13.0308"E). According to climatic data obtained from National Metrological Agency, the mean 20-year annual rainfall of the watershed ranges from 1400 to 1920 mm with unimodal pattern of distribution. The mean 20-year length of growing period (LGP) varies from 210 to 240 days. Mean long term monthly temperature minima and maxima range from 14.4 to 18.6 and 22.7 to 28.4 °C, respectively. According to Abdenna [20], Ultisols, Alfisols and Vertisols of Soil Taxonomy Soil Survey Staff [1] have been identified along toposequence of Didessa watershed. According to the WRB system [61], these soil groups correspond to Alisols, Luvisols and Vertisols, respectively [20].

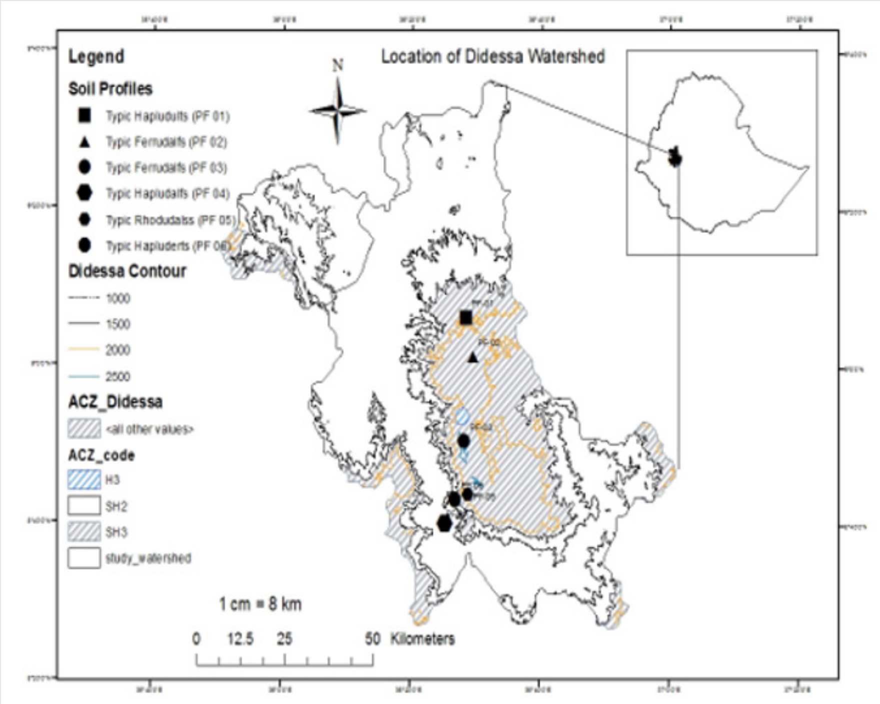


Figure 1: Alps and Climate.

b. Soil sampling from soil types

Soil samples were collected from arable cropping, grazing or short fallowing, and Eucalyptus agroforestry system from Ultisols (Typic Hapludults) and Alfisols (Typic Ferrudalfs). The land use histories from which soil samples were collected with the corresponding soil suborders are summarized in Table 1. Five composite soil samples from surface layer of 0-20 cm from two soil types were collected following standard soil sampling procedure. Thirty to forty subsamples were randomly collected from areas of uniform land uses, bulked to form composite samples, dried and homogenized. Undisturbed soil samples were collected for soil bulk density determination using a core sampler.

Table 1: Description of major land uses characteristics of the studied areas.

Land uses and codes	Soil Types	Land use history and characteristics
Eucalyptus agroforest (LS 2)	Typic Hapludults	Eucalyptus agroforest of about 10 years of age
Arable land (LS 3)	Typic Hapludults	Continuous cultivation with maize- sorghum-finger millet-noug rotation over the past 40 years
Short fallow (LS 4)	Typic Hapludults	Short fallow for 2-3 years after continuous cropping to restore soil fertility. During short fallow, the land used as grazing for livestock husbandry
Eucalyptus AgroforestS (LS 7)	Typic Ferrudalfs	The land had been under small holder traditional agriculture. As the land lost its productivity, it became under Eucalyptus agroforests since 10-15 years. Currently the land is covered by mature Eucalyptus agroforests
Arable Land (LS 14)	Typic Ferrudalfs	The land is under continuous crop cultivation with tef-millet -noug in rotation and then short fallowing for 2-3 years during which the land is used as grazing land for livestock

c. Soil physical and chemical analysis

Particle size distribution was analyzed by modified sedimentation hydrometer procedure of Bouyoucos [34]. Soil bulk density was determined by collecting undisturbed samples with a core sampler, dried at +105 °C and calculated by dividing weight of soil to volume of the core sampler. Soil pH was measured in supernatant suspension of soil to liquid ratio of 1:2.5 in H_2O (pH H_2O) and 1M KCl (pH KCl) as outlined by Reeuwijk [35]. The SOC was determined by the Walkley-Black method [35]. Exchangeable acidity was determined titrimetrically in 1MKCl solution as described by Bertsch and Bloom [36], then Al was complexed with 1M KF and exchangeable Al was then determined by titration with 0.025M HCl [35]. Exchangeable H was determined as the difference of exchangeable acidity and exchangeable Al. Titratable acidity was determined after extraction of soil mixed with barium chloride tri-ethanol-amine ($BaCl_2$-TEA) buffer solution (pH= 8.2). The CEC and exchangeable bases calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na) were determined after extraction with 1M ammonium acetate at pH -7 [35]. Concentration of Na and

K were measured by flame photometry while of Ca and Mg were measured using an ethylene di-amine tetraacetic acid (EDTA) titration method. The effective cation exchange capacity of soils (ECEC) was determined by summation of exchangeable Al, H, Ca, Mg, K and Na. The Base saturation percentage was determined by dividing sum of bases (Ca, Mg, K, and Na) to ECEC while the acid saturation percentage was calculated as dividing exchangeable acidity to the ECEC and then multiplied by 100. Available P was extracted with 0.5M $NaHCO_3$ solution [37]. and total P was extracted by digestion with sulfuric acidic and hydrogen per oxide [38]. The P concentrations were measured calorimetrically by spectrometry.

d. Soil physical and chemical properties

Physical and chemical properties of soils are summarized in Table 2. Particle size distribution was fairly similar in all soils and the textural classes range from sandy loam to clay loam. The pH values of the study soils are extremely to moderately acidic, the range being as narrow as 0.3 unit. The CEC of soils ranged from 24 to 39 cmolc kg^{-1}, medium to high suggesting that the clay mineralogy was not entirely kaolinitic clay. Base saturation ranged from 26 to 90%. The study soils had medium to high OC that ranged from 4.0 to 6.4%. The Olsen P ranged from 2 to 6 ppm, indicating P deficiency in spite of a high total P concentration [39].

Table 2: Physical and chemical properties of soils used for sorption study.

Soil code	Texture				pH		SOC	CEC	Ex. AC	Ex. Al	Ex. H	T. AC	Ex. Ca	Ex. Mg	Ex. Na	Ex K	PBS	Total P	Avail P
	Sand	Silt	Clay	Class	H_2O	KCl	%		cmolckg^{-1} soil								%	mg kg^{-1}	ppm
LS-2	57	23	20	SL	4.8	3.6	6.4	39	8.2	8.0	0.2	41.6	1.39	1.39	0.1	0.18	27.2	2211	2.3
LS-3	53	27	20	SL	5	3.9	4.8	37	1.4	1.4	trace	32.9	8	2.66	0.1	2.28	90.3	2395	6
LS-4	47	27	26	SL	4.9	3.7	5.2	36	2.2	2.2	trace	33.3	6.28	3.77	0.12	1.2	83.8	2692	2.3
LS-7	53	25	22	SCL	4.7	3.6	5.7	24	9.3	8.8	0.57	40.6	1.35	1.35	0.13	0.21	26.4	1664	2.3
LS-14	43	25	32	CL	5	3.6	4	34	4.5	4.4	0.09	27.2	5.1	3.81	0.1	0.67	68.4	2185	2.3

Example: AC = Exchangeable Acidity; Ex. Al = Exchangeable Al3+; Ex. H = Exchangeable H+; T.AC. = Titratable (total) Acidity, SEB = Sum of Exchangeable bases; PBS = Percent Exchangeable Base Saturation; PAS = Percent Exchangeable Acid Saturation.

e. Soil-lime incubation experiment

Five representative composite soil samples collected from Ultisols and Alfisols from Eucalyptus plantation, arable cropping, grazing (short fallow) lands were subjected to liming. Twenty to thirty subsamples were collected and bulked to form a composite sample for representative soil samples used for liming study. The five lime treatments were equivalent to 0, 50, 100, 150 and 200% of the lime requirement estimated from of exchangeable acidity of the soils Table 3. The soils were placed into 250 ml capacity glass funnels and watered to field capacity and incubated for 60 days in a chamber at 20 °C in laboratory. The liming material is high quality grade (99.99%). The soils were watered weekly. After 60 days of incubation, the soils were air dried and analyzed for chemical properties particularly pH (H_2O), exchangeable acidity, exchangeable Al, and exchangeable bases and the results were reported on dry weight basis.

Table 3: Lime treatments on the basis of percent exchangeable Al for five soils from Ultisols and Alfisols of Didessa watershed of humid Wester Ethiopia.

Field code	Alex	Amount of $CaCO_3$ (mg/100g soil) equivalent to exchangeable Al (cmolc kg^{-1} soil)				
	cmolc kg^{-1} soil	0%	50%	100%	150%	200%
LS-2	8.2	0	205	410	615	820
LS-3	1.39	0	35	70	104	139
LS-4	2.18	0	55	109	164	218
LS-7	8.75	0	219	438	656	875
LS-14	4.43	0	111	222	332	443

f. Phosphorus sorption experiment

The representative soil samples limed to neutralize the exchangeable acidity and the unlimed soil samples were used in a P adsorption study according to the procedure outlined by Sharpley [40]. One-gram soil samples were weighed and placed into centrifuge tubes with capacity of 40 ml with replications. A range of P solutions (0, 10, 20, 30, 40, 50, 60, 70, and 80 mg l^{-1}) were prepared from stock P solution (100 mg l^{-1}) of KH_2PO_4 in 1L 0.01M $CaCl_2$. $2H_2O$ as supporting electrolyte. The centrifuge tubes with soils and added P were filled to a final volume of 25 ml. Two drops of chloroform were added to retard microbial activities. The final concentrations were equivalent to 0, 250, 500, 750, 100, 1250, 1500, 1750 and 2000 mg P kg^{-1} soil. The soil and P mixture were shaken at 10 rpm on horizontal shaker for 24 hours and then centrifuged at 3000 rpm for 15 minutes and the clear supernatant was filtered through Whatman No 42 filter paper. The filtrates were analyzed for P as per the ascorbic acid method Murphy and Riley [41] and P concentration was measured at 880 nm absorbance by UV/VIS spectrometry. The P in control treatments was taken into account and adsorbed P was calculated as mg kg^{-1} soil. The P adsorption data were fitted into Langmuir adsorption model [40]. Langmuir adsorption model of the form:

(X)=((K*C*bmax)/(1+K*C)) and the linearized form (C/((X/M)))=(1/kbmax)+(c/bmax) were used, where c is the equilibrium solution P concentration (mg P L^{-1}), x/m is the mass of P adsorbed per unit mass of soil (mg kg^{-1} soil), k is a constant related to bonding energy of P to the soil, and b is the maximum P adsorption (mg kg^{-1} soil). A plot of c/(x/m) versus c were drawn and the values of bmax and k were obtained from the slope (1/b) and the intercept (1/kb), respectively. The equilibrium P concentration (EPC0, mg P/L), defined as the solution P concentration supported by a soil sample at which no net sorption or desorption occurs, was calculated as the x-intercept of linearized form of isotherm curve at lower part of concentration curves. Moreover, the SPR at 0.1 and 0.2 mg l^{-1} equilibrium solution concentration were derived from adsorption versus equilibrium concentration drawn to 0.1 and 0.2 mg l^{-1}, respectively.

g. Statistical data analysis

Statistical analysis of data to determine the goodness of fit to adsorption equations and analysis of variance were carried out using SPSS software version 20.5. Statistical significance level was determined at 0.01 and 0.05 (risk level). Correlation analysis was carried out to determine association between soil properties (physical and chemical properties) and sorption parameters. Independent sample t-test was used to determine effect of soil types and lime treatment on sorption parameters.

Results and Discussion

a. Optimum lime to neutralize exchangeable aluminum

The chemical properties of soils after 60 days of lime incubation are indicated in Table 4. Liming acid soils increased soil pH, exchangeable Ca, and base saturation on the basis of ECEC, and decreased Alex and acid saturation. Exchangeable Al decreased with increased pH and was fully precipitated at pH of 5.1 to 5.2 Table 4. Optimum lime requirement that fully precipitate exchangeable Al varied from 5.37 to 11.41-ton ha-1 Table 5 and was directly proportional to Alex. The limed soils used for P sorption study had trace amount of exchangeable acidity and the pH (H_2O) ranged from 5.36 to 6.7. The optimum lime requirement to neutralize exchangeable Al was compared with previous liming studies conducted in Ethiopia. For example, Achalu [27] recommended optimum lime rate of 7-ton $CaCO_3$ ha^{-1} and Hirpha [42] determined 4.4-ton $CaCO_3$ ha^{-1} for acid soils of humid tropical Ethiopia. Mekonin [30] found optimum lime rate of 2.2-ton $CaCO_3$ ha^{-1} while Asmare [31] recommended 3.5-ton $CaCO_3$ ha^{-1} for acid soils of North Western Ethiopia.

Table 4: Effect of lime application on soil chemical properties.

Soil code	$CaCO_3$	pH	Ex. Al	∑ Bases	ECEC	PBS
	cmolc kg^{-1} soil	H_2O	cmolc kg^{-1} soil			%
LS-2	0	4.2	6.7	1.67	8.37	20
	4.1	4.8	2.8	5.67	8.47	67
	10.4	5.1	0	7.67	7.67	100
	20.8	5.6	0	17.67	17.67	100
	31.4	6.7	0	20.67	20.67	100
LS-3	0	4.9	1.1	9.04	10.14	89
	3.3	5.1	0.7	10.04	10.74	93
	8.4	5.1	0.1	11.04	11.14	99
	16.7	5.2	0	11.04	11.04	100
	25	5.4	0	14.04	14.04	100
LS-4	0	4.8	1.7	9.09	10.79	84
	4.1	5	0.3	10.09	10.39	97
	10.2	5.5	0	13.09	13.09	100
	20.4	5.9	0	20.09	20.09	100
	30.5	6.3	0	22.09	22.09	100
LS-7	0	4.5	5.5	1.69	7.19	24
	2.7	5.1	3.5	4.69	8.19	57
	6.8	5.2	0.3	8.69	8.99	97
	13.6	6	0	14.69	14.69	100
	20.4	6.4	0	21.69	21.69	100

LS-14	0	5	3.1	7.58	10.68	71
	2.4	5.1	1.4	14.58	15.98	91
	5.9	5.3	0	15.58	15.58	100
	11.9	5.5	0	16.58	16.58	100
	17.9	6.3	0	20.58	20.58	100

Example: Al=Exchangeable Al, Ex. Ca=Exchangeable Ca, Σ Bases=Summation of Exchangeable Bases, ECEC=Effective Cation Exchange Capacity, BS=Base Saturation, AS= Acid Saturation.

Table 5: Amount of optimum calcium carbonate needed to increase soil pH of soil after incubation.

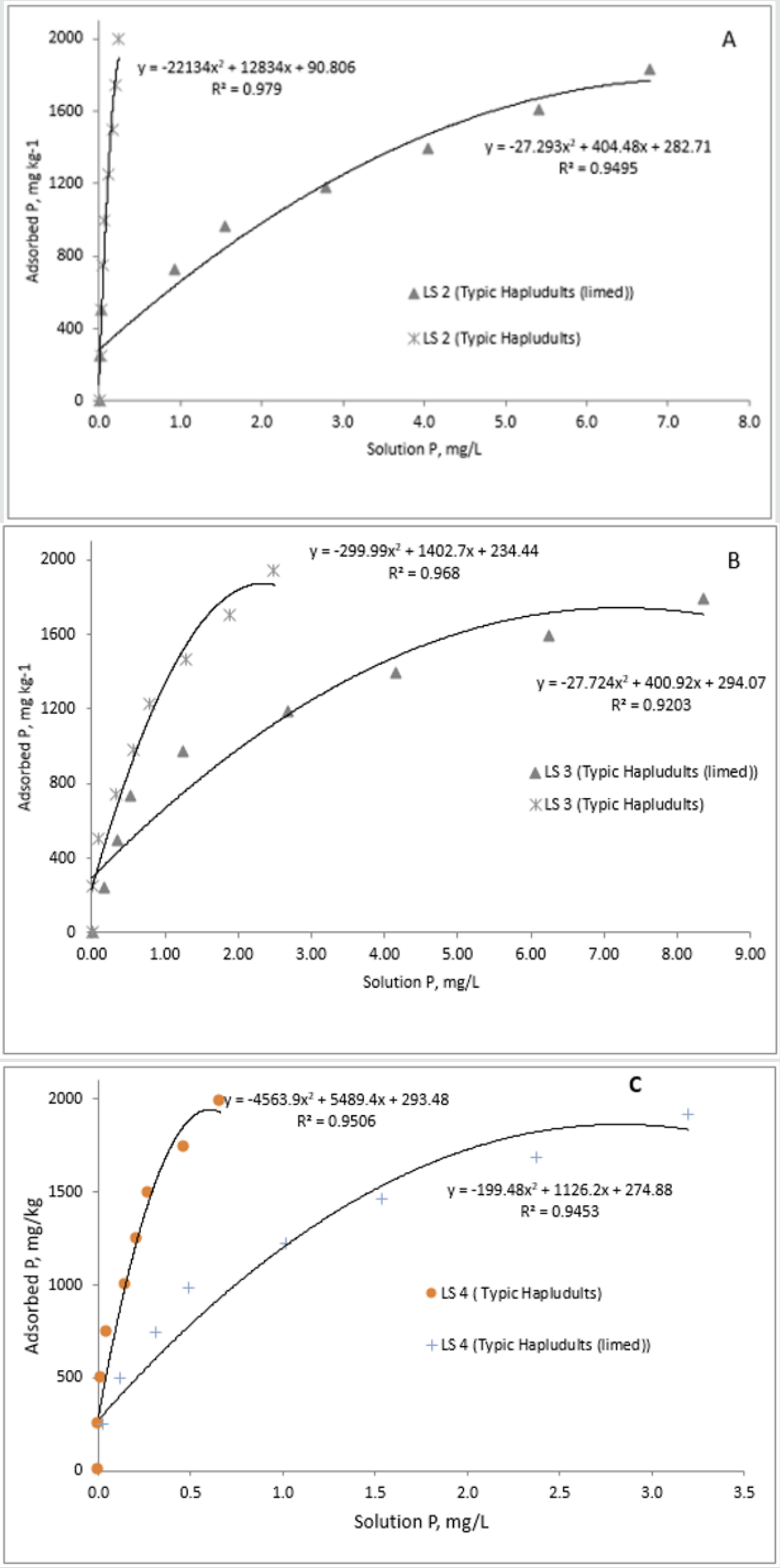
No	Soil samples	pH	$CaCO_3$, mg $100g^{-1}$ soil	$CaCO_3$, kg/ha
1	LS-2	6.7	1570	34,540
2	LS-3	5.36	332	7,300
3	LS-4	6.25	1250	27,500
4	LS-7	6.42	1524	33,530
5	LS-14	6.27	1020	22,440

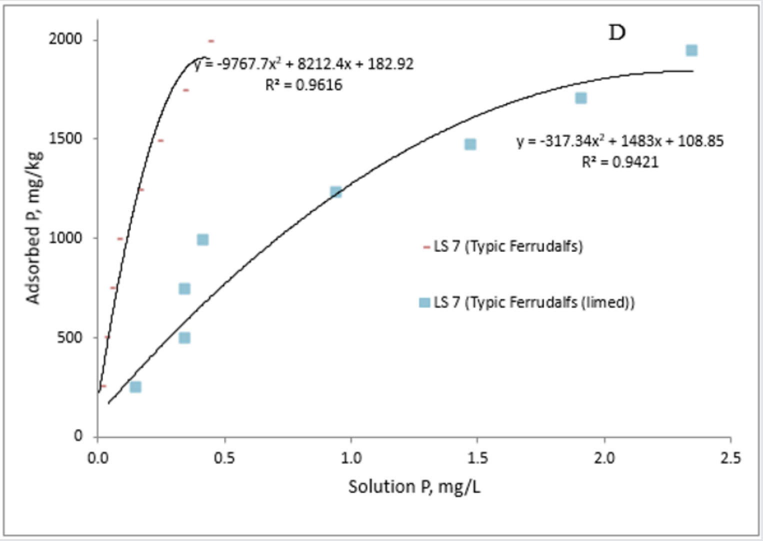
b. Equilibrium concentration and pattern of phosphorus sorption isotherms

The patterns of equilibrium P concentrations of the soil extracts are indicated in Figure. 2. Concentrations of P in the extract soils to which P solution was not added were nearly zero among most soils. With incremental rates of P addition, P in the soil extract increased, but with varying extent among soil types and lime treatment. Unlimed Typic Hapludults (LS-2 and LS-4) and Typic Ferrudalfs (LS-7) showed subtle increase of P in soil extracts and maximum P concentration of these soils ranged from 0.24 mg l^{-1} in LS-2 to 0.44 mg l^{-1} in LS-7, even though a solution containing 80 mg P l^{-1} had been added. Whereas unlimed Typic Hapludults (LS-3) and Typic Ferrudalfs (LS-14) showed some more increase of P concentration in the soil extracts which ranged from 0.24 mg l^{-1} in LS-14 to 2.5 mg l^{-1} in LS-3 soils. Lime treatments increased maximum solution P concentration of four out of five soils treated with lime (LS-2, LS-3, LS-4 and LS-7) that ranged from 2.35 mg l^{-1} in LS-7 to 8.37 mg l^{-1} in LS-3 while liming slightly decreased P concentration of the soil extract of LS-14.

Person correlation analysis revealed that the solution P max concentrations for limed soils was positively correlated with percentage silt and clay fractions, initial pH (H_2O and KCl), and CEC, while it was negatively correlated with percentage sand fraction, exchangeable acidity and Al before liming, and percentage acid saturation and SOC of soils. However, none of these soil parameters were significantly (P>0.05) correlated with solution P max concentration before liming. Similar analysis of person correlation analysis also revealed that the solution P max concentrations for unlimed soils was positively correlated with sand and silt fractions, initial pH (H_2O and KCl) and SOC, while it was negatively correlated with clay fraction, final pH after lime treatment, initial exchangeable acidity and Alex, and percentage acid saturation of soils. However, similar to unlimed soils, none of these soil parameters were significantly (P>0.05) correlated with solution P max concentration after liming.

The patterns of P sorption for unlimed and limed soils are different. The patterns of P sorption isotherms for limed soils represent the H type with sorption maximum (with plateau formation) Figure. 2. The patterns for P sorption isotherm curves for unlimed soils for both Typic Hapludults and Typic Ferrudalfs are also H type (high affinity sorption) but without sorption maximum (without plateau formation) with incremental concentration of P[43]. The H type sorption curves of unlimed soils indicate that all reactive P adsorption sites on colloidal surfaces were not saturated with P (continuous site affinity). The high affinity of soils for P sorption was due to soil reaction and degree of pedogenesis. The soils have low pH, low exchangeable Ca and Mg, high reserve and exchangeable acidity Table 2. Moreover, the soils had clay and oxide coatings, and mineral concretions (sesquioxides) with dark brown (7.5YR3/2) to dark reddish brown (5YR3/2) topsoil color and even redder (2.5YR4/4–5/6) in the subsoil, indicating presence of oxides and hydrous oxides of Fe and Al [20]. Strong correlations between sesquioxides of Fe and Al (goethite, gibbsite, and hematite content) with P binding have been commonly reported in tropical and subtropical soils [3,8,44-46]. The binding affinity of sesquioxides, and Fe and Al on structural frames of soils is largely determined by soil pH [3]. Most oxides of Al have maximum adsorption capacity between pH 4 and 5, while Fe oxides bind P most strongly between pH 3 to 4. The limed soils had a pH range from 5.4 to 6.7 and the increased soil pH by 0.5 to 1.9 units had obviously and markedly decreased the P sorption tendency of soil. The H type P sorption patterns with bmax for lime treated soils in the present study are similar with the report of Zinabu and Wassie [13] for sorption pattern of some soils of Southern Ethiopia. Significant negative correlation between bmax and SPR with pH, titratable and exchangeable acidity, and exchangeable bases was observed. This is in agreement with many reports from tropical soils [8,47]. Low pH and high concentration of Fe and Al oxides contribute to high and very high P sorption capacities [8,47].


A
y = -22134x² + 12834x + 90.806
R² = 0.979
y = -27.293x² + 404.48x + 282.71
R² = 0.9495
LS 2 (Typic Hapludults (limed))
LS 2 (Typic Hapludults)
Adsorbed P, mg kg-1
Solution P, mg/L
B
y = -299.99x² + 1402.7x + 234.44
R² = 0.968
y = -27.724x² + 400.92x + 294.07
R² = 0.9203
LS 3 (Typic Hapludults (limed))
LS 3 (Typic Hapludults)
Adsorbed P, mg kg-1
Solution P, mg/L
C
y = -4563.9x² + 5489.4x + 293.48
R² = 0.9506
y = -199.48x² + 1126.2x + 274.88
R² = 0.9453
LS 4 (Typic Hapludults)
LS 4 (Typic Hapludults (limed))
Adsorbed P, mg/kg
Solution P, mg/L



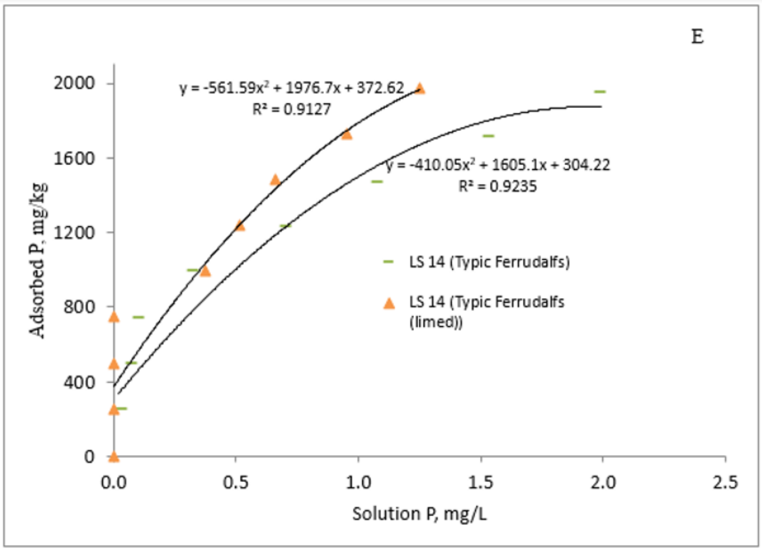


Figure 2: Pattern of adsorption curves of different soils treated with and without lime treatment.

c. Mean phosphorus sorption parameters

The linearized Langmuir sorption equations for unlimed and limed soils are summarized in Table 6. The high R2 values indicate that curves fit well to the Langmuir model. The sorption parameters for individual soils derived from the linearized Langmuir sorption equations are presented in Table 7.

Table 6: Linearized Langmuir equations for lime treated and untreated soils.

Soil code	Without lime treatment		With lime treatment	
	Langmuir equations	R^2	Langmuir equations	R^2
LS 2	y = 0.0003x + 0.0004	0.946	y = 0.0015x + 0.0004	0.983
LS 3	y = 0.0006x + 0.0015	0.977	y = 0.0028x + 0.002	0.955
LS 4	y = 0.0005x + 0.0004	0.971	y = 0.0009x + 0.0022	0.964
LS 7	y = 0.0004x + 0.0004	0.988	y = 0.0005x + 0.004	0.8986
LS 14	y = 0.0006x + 0.0009	0.982	y = 0.0006x + 0.0006	0.9214

Table 7: Phosphorus sorption parameters for Langmuir model.

Soil code	Unlimed soils					Limed soils				
	EPC0 (mg/l)	SPR0.1 (mg/kg)	SPR0.2 (mg/kg)	Smax (mg/kg)	K	EPC0 (mg/l)	SPR0.1 (mg/kg)	SPR0.2 (mg/kg)	Smax (mg/kg)	K
Ls 2	0	1153	1772	3333	6	0.008	299	369	2000	1
Ls 3	0.01	407	622	2000	2.5	0	154	312	1429	1.2
Ls 4	0.01	879	1281	2000	12.5	0.016	396	632	1667	0.2
Ls 7	0.01	938	1456	2500	8	0.01	126	372	3333	0.6
Ls 14	0.014	563	688	2000	5	0.012	275	521	3333	1

d. Effects of soil types on sorption parameters

Maximum Sorption Capacity: The mean Langmuir sorption capacity (bmax) ranged from 2791 mg kg^{-1} soil for Typic Ferrudalfs to 2072 mg kg^{-1} soil for Typic Hapludults Table 8. However, the difference is not statistically significant. The similarity of soil chemical and physical properties among the two soils types seems to be the main cause of the lack of difference for the maximum sorption capacity of soils. Similar magnitude of bmax of 2129 mg kg^{-1} for Brazilian Rhodic Eutrudalfs and the 577 mg kg^{-1} of bmax for Rhodic Hapludults were also reported by Compose [46]. Dubus and Becquer [11] also found comparable bmax of 2246 mg kg^{-1} for the New Caledonian Island soils while Gichangi [8] found out lower magnitude of bmax that range from 192 to 909 mg kg^{-1} for some South African Ferralsols.

i. Equilibrium P concentration at zero sorption (EPC0): The EPC0 was very low for the studied soils Table 7. The mean EPC0 was 0.012 mg l^{-1} for Typic Ferrudalfs and 0.007 mg l^{-1} for Typic Hapludults Table 8. The EPC0 of the current study soils are comparable with most EPC0 values of eighty soil samples from Alfisols of NW Ethiopia [48]. He reported EPC0 in the ranges of 0.015 to 0.227 mg l^{-1} where the majority of the EPC0 is less than 0.1 mg l^{-1}. The EPC0 value of Typic Hapludults and Typic Ferrudalfs are lower than is commonly published for European soils. Hartikainen [49] reported values for EPC0 that varied from 0 to 3.36 mg l^{-1} for representative European soil types with one soil having 10 mg l^{-1}. In that study the EPC0 value of zero was determined for very P deficient acidic soils, and exceptionally high EPC0 of 10 mg l^{-1} for highly fertilized soils. Peltovurori [50] also reported EPC0values ranging from 0.07 to 1.82 mg l^{-1} for agricultural surface soils from Finland, the highest values occurring in excessively fertilized soils.

A wide variation of P sorption and desorption results in a given soil can be measured depending on experimental conditions. Decreased salt concentration (ionic strength) of the extractant ($CaCl_2$) and increased solution to soil ratio usually increase desorption and decrease sorption [51]. For example, Yihenew [48] conducted extraction of P in solution to soil ratio of 17:1 in 0.01M $CaCl_2$ supporting electrolyte; Hartikainen [49] conducted extraction in solution to soil ratio of 50:1 with no supporting electrolyte. These variations of the experimental condition under which these experiments were conducted contribute to the variation in quantity-intensity plots and parameters derived from the curves like EPC0. Some of the variation of the EPC0 derived from quantity-intensity curve of Yihenew [48]with current results could be due to difference in the solution to soil ratios but since the supporting electrolyte is the same, the magnitude of the results is likely similar [51].

ii. Standard phosphorus requirement: The mean SPR for unlimed Typic Ferrudalfs and Typic Hapludults to attain equilibrium P concentration of 0.2 mg l^{-1} ranged from 759 and 831 mg kg^{-1}, respectively, Table 8. The SPR0.2 of Typic Ferrudalfs and Typic Hapludults are comparable and not significantly different ($p>0.05$). The SPR0.2 values are higher than the SPR0.2 for some other tropical and subtropical soils. Tekalign and Haque [15] reported SPR0.2 ranging from 84 to 550 mg kg^{-1} for Nitosols, 105 to 600 mg kg^{-1} for Vertisols, and 540 to 580 mg P kg-1 for Luvisols of Ethiopia. Many authors also reported lower SPR for some southern Ethiopian soils Zinabu [52], for some Kenyan soils Kisinyo [19] , West African savanna [16], South African [8] and Central African soils [53]. The SPR0.2 of Typic Hapludults and Typic Ferrudalfs of the present soils are lower than the SPR0.2 of humid and humic Andosols [15] being 1200 and 1500 mg kg^{-1}, respectively.

e. Effect of liming on P sorption parameters

The effects of optimum liming on P sorption parameters are presented in Table 8. The mean bmax for limed and unlimed soils were 2367 and 2352 mg kg^{-1}, respectively. Liming increased bmax of Ferrudalfs while it decreased the bmax of Typic Hapludults. The mean SPR0.2 for unlimed and limed soils was 441 and 1164 mg kg^{-1}, respectively. Lime treatment decreased SPR through its decreasing affinity for P sorption through increasing soil pH and precipitation of exchangeable Al. Similar pattern of liming effect was observed between the two soil types. Liming the soils substantially increased the solution P max concentration and did not influence bmax very much Table 8. This is due to decreased bonding strength of added P with liming. The calculated P affinity of unlimed and limed soils for P as indicated K values confirmed the decreased bonding strength of added P to the soils with liming Table 7.

Table 8: Effects of soil types and lime amendments on Langmuir adsorption parameters and soil P requirements (mg P kg^{-1} soil).

Variables	EPC0 (mg/l)		SPR0.1 (mg/kg)		SPR0.2 (mg/kg)		Smax (mg/kg)		k	
Soil types	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
Typic Ferrudalfs	0.0116ns	0.0009	476ns	179	759.3ns	241.1	2792ns	329	3.7ns	1.76
Typic Hapludults	0.0073ns	0.0025	548ns	157	831.3ns	234.8	2072ns	270	3.9ns	1.91
Lime treatment										
Unlimed	0.0089ns	0.0023	788a	134	1164a	2224	2367ns	260	6.8a	1.68
Limed	0.0092ns	0.0026	250b	50	441b	59	2352ns	411	0.8b	0.18

EPCO=Equilibrium P concentration at net zero sorption; SPR0.1=Standard phosphorus requirement that bring equilibrium phosphorus concentration to 0.1 mg/l; SPR0.2=standard phosphorus requirement that bring equilibrium phosphorus concentration to 0.2 mg/l; b_{max}=Langmuir adsorption maximum; k=sorption affinity; ns=none significant at P value of 0.05; means followed by the same letter within a column are statistically none significant at P value of 0.01 and 0.05 using independent sample T-test.

The decreased SPR with lime treatment in current study is in agreement with many studies that indicated decrease of P sorption as the pH raises from 4.0 to 7.0 [17]. Lime treatment probably increased availability of P through decreased sorption to oxides and clay minerals [18]. In some humid Brazilian Ultisols, Sato [47] also reported decreased P sorption with increased pH at equilibrium solution P concentration below 3 mg l^{-1}. He reported decreased P adsorption by 21% as pH increased from 4.7 to 5.9 and by 34% as pH increased further to 7.0 through liming. In our study the amount of lime required to bring soil pH to neutral pH varied from 7.3 to 34.5-ton ha^{-1}. These are quite large amounts of lime which can constrain the practicality of liming for increased availability of P. Such large amount of lime needed to increase the pH and P availability can be reduced by changing method of lime determination from pH-based lime determination to exchangeable Al based lime recommendation [21].

According to Sanchez and Goro [54] the soils with SPR0.2 greater than 150 mg P kg^{-1} for tropical soils are categorized as high P fixing soils and the current soils by far exceed this threshold value, thus representing high P fixing soils. According to SPR0.2, the current soils need huge amounts of external P fertilizer to bring soil solution P concentration to attain 0.2 mg l^{-1} for optimum P availability. The high SPR0.2 is inconveniently high even in the long run for small holder farmers. High SPR0.2 calls for localized application of P to create pocket of high concentration for crop uptake or use of liming to decrease SPR. Some crops like maize, upland rice, cabbage, sweet potato, and sorghum could also thrive well at 0.1 mg l^{-1} [54]. Thus, the use of 0.1 mg l^{-1} reduces the SPR for low phosphate tolerant crop varieties. Low income community, who could not afford to buy the high SPR to achieve equilibrium P concentration of 0.2 mg l^{-1}, can use the SPR that can achieve equilibrium P 0.1 mg l^{-1} with some low tolerant crop varieties. Considering about 5% of soil volume to the depth of 15 cm plow layer to be covered with band P fertilizer application, the SPR0.1 corresponds to 39 and 49 kg ha^{-1} while the SPR0.2 corresponds to 63 and 75 kg ha^{-1} for Typic Ferrudalfs (ρb=1.1 g cm-3) and Typic Hapludults (ρb=1.1 g cm-3), respectively. The SPR0.1 corresponds to 67 and 21 kg ha^{-1} while the SPR0.2 corresponds to 99 and 37 kg ha^{-1} for unlimed and limed, respectively.

In the study area, band application of 30 kg P ha^{-1} for maize [55], blanket application of 20 kg P ha^{-1} for faba bean, field pea, soybean, sweet potato, and tef [56-58], 22 kg P ha^{-1} for millet, sunflower and haricot bean e[56,57&59], 33 kg P ha^{-1} for sorghum [57] and 41 kg P ha^{-1} for hot pepper [58] production were recommended 20 years ago. Most of the recommended P fertilizers for crop production are lower than the P fertilizer required to achieve solution P concentration of 0.1 and 0.2 mg l^{-1} for band application in this finding. For example, currently, it is hardly possible to grow maize with this P fertilizer recommendation in Ethiopia. The previous on-farm research recommendation for maize production accounts to about 61% for Typic Hapludults and 78% for Typic Ferrudalfs to achieve the optimum P fertilizer required to attain equilibrium solution P concentration of 0.1 mg l^{-1}. It accounts for about 40% for Typic Hapludults and 48% for Typic Ferrudalfs to achieve the optimum P fertilizer required to attain equilibrium solution P concentration of 0.2 mg l^{-1}. Under lime treatment the previous on-farm research recommendation for maize production accounts to about 45% for unlimed and 142% for limed soils to achieve the optimum P fertilizer required to attain equilibrium solution P concentration of 0.1 mg l^{-1}. It accounts for 30% and 80% to achieve the optimum P fertilizer required to attain equilibrium solution P concentration of 0.2 mg l^{-1} for unlimed and limed soils, respectively. According to this P sorption study, the previous research recommendation could not elevate the solution P concentration to 0.1 to 0.2 mg l^{-1} for the soil's types without optimum lime application [60-62]. This is most likely the reason for the common observation that small rates of P do not increase yield for most agronomic crop production in Ethiopia. Thus, under optimum lime application rate, the previous research recommendation could sufficiently supply the equilibrium solution P concentration of 0.1 mg l^{-1} for suboptimal P availability and requires about extra P fertilizer for optimum P availability to attain equilibrium solution P concentration of 0.2 mg l^{-1}.

iii. Effect of land uses on P sorption characteristics: Difference in the land use system affects P sorption characteristics of soils Figure 2. Typic Hapludults from eucalyptus agroforestry (LS-2) system has higher $b_{max,}$ SPR and K as compared to the same soil types from arable cropping land (LS-3) and short fallow land (LS-4) systems. Typic Hapludults from agroforestry system has higher soil acidity compared to the same soil types from arable cropping and short fallow land use systems. Moreover, Typic Ferrudalfs from agroforestry (LS-7) has higher b_{max}, SPR and K as compared to the same soil type from arable cropping (LS-14) land use system. Despite variation of soil properties over short lateral distances across land uses, difference in P sorption characteristics of the soils are presumably caused by difference in the land use history Table 1. Eucalyptus agroforestry system of land uses have generally higher soil acidity and higher sorption of applied P to the soil system. Farming communities in the study area usually assign impoverished soils to agroforestry system or land not suitable for arable cropping system. Thus, the higher P sorption capacity of the soils under eucalyptus agroforestry systems might be due to slight difference in the inherent soil properties or due to the impoverishing effect of eucalyptus plantation on chemical and biological properties of soils. In fact, this requires further investigations.

Conclusion and Recommendation

The study revealed that the Typic Ferrudalfs (Alfisols) and Typic Hapludults (Ultisols) in Ethiopia have high P adsorption capacities. However, the bmax, SPR, EPC0 and phosphate binding affinity (k) were not significantly different between the two soil types. The individual soils require 7.3 to 35 tons ha^{-1} calcium carbonate to fully precipitate exchangeable Al and to increase soil pH close to neutrality. Lime treatment of soils significantly decreased SPR from 1164 to 441 mg kg^{-1} and phosphate binding affinity of soils. The EPC0 of the soil types and lime treatments were very low which is a typical feature of weathered tropical soils receiving little P fertilization and contain high concentration of Fe and Al oxides and hydroxides. The SPR and binding affinity significantly decreased with liming but the trend of maximum sorption of soils varied with soil type. The study suggested that Typic Hapludults and Typic Ferrudalfs that cover several hundreds of square km in Ethiopia require similar P fertilizer rate and management strategy for sustainable soil uses for crop production. Besides decreasing the soil acidity problems of Typic Ferrudalfs and Typic Hapludults, the use of optimum lime rates for each soil type are recommended to decrease the SPR of soils and increase P bioavailability. The SPR of the soils cannot satisfy the agronomic demand of most agronomic crops under limed and unlimed soils. Due consideration should be given to develop P fertilizer recommendation rates for limed and unlimed soils for optimum P availability for sustainable soil productivity of Typic Ferrudalfs and Typic Hapludults in Ethiopia.

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